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Optical Lattice Gases of Interacting Fermions

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FINAL PERFORMANCE REPORT

Contract/Grant Title: Optical Lattice Gases of Interacting Fermions
Contract/Grant #: FA9550-12-1-0079
Technical contact: Dr. Tatjana Curcic, (703) 696-6204

Summary of Major Accomplishments

The theoretical research supported by this grant focused on discovering new phases of quantum matter for ultracold fermionic atoms or molecules confined in optical lattice potentials. It has produced over 18 papers published or under peer review in journals such as Physical Review Letters and Nature Communications, including a review paper on the orbital physics of cold atoms in optical lattices [1] and a book chapter on topological insulators of cold atoms [14]. A few significant results are highlighted below.

1. *Novel phases of cold atoms on higher orbital bands*. The research team discovered theoretically a "topological ladder", i.e. a ladder-like optical lattice containing ultracold atoms in higher orbital bands [15] in the absence of artificial gauge fields or spin-orbit coupling. This topological insulator phase turns into a topological superconductor featuring Majorana zero modes at the boundaries. In addition, the research team derived and solved a new spin-orbital exchange model for strongly interacting fermions on the p-band of a two-dimensional optical lattice [6]. They showed that the spin-orbit exchange frustrates the development of long-range spin order, and gives rise to an exotic, spin-disordered ground state with ferro-orbital order. The two-dimensional system dynamically decouples into individual Heisenberg spin chains, each realizing a Luttinger liquid accessible at higher temperatures compared to atoms confined to the s-band. The research team also extended the investigation of orbital physics into electronic oxide interfaces [12].

2. *Chiral states of interacting quantum matter: notions of chiral Bose liquid for bosons and center-of-mass chiral p-wave superfluidity/superconductivity for fermions*. The research team predicted the existence of a chiral Bose liquid phase, a surprising quantum phenomenon occurring at intermediate temperatures which differs from the familiar superfluid or normal phase of interacting bosons and has not been anticipated in condensed matter physics [13]. Furthermore, they demonstrated that a p-wave chiral superfluid of fermionic atoms can arise from spin-singlet pairing between even and odd parity orbital bands [9]. This is again surprising because the conventional paradigm required spin-triplet pairing. Chiral p-wave superfluids, as found in liquid helium-3 and proposed to describe Sr_2RuO_4 superconductors, are a prototypical topological superfluid. Despite its conceptually different origin, the state found by the research team for s-wave interacting Fermi gases has topological properties similar to the conventional chiral p-wave state. These include a non-zero Chern number and the appearance of chiral fermionic zero modes bounded to domain walls [3].

3. *Weyl superfluid*. The research team discovered that a Weyl superfluid state can arise as a low temperature stable phase in a three-dimensional dipolar Fermi gas in a rotating

external field [7]. A Weyl superconductor or superfluid is a gapless topological state of matter that features nontrivial (hedgehog) topology in momentum space, Weyl fermionic excitations, exotic surface states, and transport anomalies. The finite temperature phase diagram obtained indicates that Weyl superfluid is within the experimental scope for dipolar Fermi gases [7]. The research team also further demonstrated that Weyl superconductors can be engineered in periodic structures of conventional superconductors and magnetic materials [2]. Weyl fermion is a concept originated from the early years of particle physics and quantum field theory.

4. *New edge modes in periodically driven cold atoms on optical lattice*. The research team discovered a new class of topological phenomena in time-modulated optical lattices, the counter-propagating π modes, which have no static analog and lie outside the known periodic table of topological insulators and superconductors [11]. In addition, they achieved an intuitive understanding of such Floquet edge modes by an in-depth analysis of the harmonically driven Hofstadter model including edge state wave function in both the time and the frequency domain and its stability against disorder [10].

These results unequivocally proved the central mission of this research project that interacting cold atoms in optical lattices provide unique opportunities for exploring new forms of quantum matter, which previously had seemed hard or impossible to achieve in traditional solids.

Publications stemming from the research effort:

1. Xiaopeng Li, W. Vincent Liu, “Physics of higher orbital bands in optical lattices: a review,” arXiv:1508.06285 (2015).
2. Ahmet Keles, Erhai Zhao, “Weyl nodes in periodic structures of superconductors and spin active materials,” arXiv:1506.05166 (2015).
3. Bo Liu, Xiaopeng Li, Randall G. Hulet, W. Vincent Liu, “Detecting π-phase superfluids with p-wave symmetry in a quasi-1D optical lattice,” arXiv:1505.08164 (2015).
4. Bo Liu, Xiaopeng Li, W. Vincent Liu, “Orbital hybridized topological Fulde-Ferrel superfluidity in a noncentrosymmetric optical lattice,” arXiv:1505.07444 (2015).
5. Zhi-Fang Xu, Xiaopeng Li, Peter Zoller, W. Vincent Liu, “Spontaneous quantum Hall effect in an atomic spinor Bose-Fermi mixture,” *Phys. Rev. Lett.* 114, 125303 (2015).
6. Zhenyu Zhou, Erhai Zhao, W. Vincent Liu, “Spin-orbital exchange of strongly interacting fermions on the p-band of a two-dimensional optical lattice,” *Phys. Rev. Lett.* 114, 100406 (2015).
7. B. Liu, X. Li, L. Yin, W. V. Liu, “Weyl Superfluidity in a Three-Dimensional Dipolar Fermi Gas,” *Phys. Rev. Lett.* 114, 045302 (2015).
8. X.-J. Liu, Z.-X. Liu, K. T. Law, W. Vincent Liu, T. K. Ng, “Chiral Topological Orders in an Optical Raman Lattice,” arXiv:1405.3975 (2014).
9. B. Liu, X. Li, B. Wu, W. Vincent Liu, “Chiral superfluidity with p-wave symmetry from an interacting s-wave atomic Fermi gas,” *Nature Communications* 5, 5064 (2014).

10. Zhenyu Zhou, Indubala I. Satija, and Erhai Zhao, "Floquet edge states in a harmonically driven integer quantum Hall system," *Phys. Rev. B* 90, 205108 (2014).
11. Mahmoud Lababidi, Indubala I. Satija, and Erhai Zhao, "Counter-propagating edge modes and topological phases of a kicked quantum Hall system," *Phys. Rev. Lett.* 112, 026805 (2014).
12. Xiaopeng Li, W. Vincent Liu, Leon Balents, "Spirals and skyrmions in two dimensional oxide heterostructures," *Phys. Rev. Lett.* 112, 067202 (2014).
13. Xiaopeng Li, Arun Paramekanti, Andreas Hemmerich & W. Vincent Liu, "Proposed formation and dynamical signature of a chiral Bose liquid in an optical lattice," *Nature Communications* 5, 3205 (2014).
14. Indubala I. Satij, Erhai Zhao, "Topological Insulators with Ultracold Atoms," Chapter 12, *New Trends in Atomic and Molecular Physics*, edited by M. Mohan, Springer Series on Atomic, Optical, and Plasma Physics Vol. 76, 201 (2013).
15. Xiaopeng Li, Erhai Zhao, W. Vincent Liu, "Topological states in a ladder-like optical lattice containing ultracold atoms in higher orbital bands," *Nature Communications* 4, 1523 (2013).
16. Xiaopeng Li, W. Vincent Liu, "Orbital phases of fermions in an asymmetric optical ladder," *Phys. Rev. A* 87, 063605 (2013).
17. Satyan G. Bhongale, Ludwig Mathey, Erhai Zhao, Susanne F. Yelin, Mikhail Lemeshko, "Quantum phases of quadrupolar Fermi gases in optical lattices," *Phys. Rev. Lett.* 110, 155301 (2013).
18. Yong Xu, Zhu Chen, Hongwei Xiong, W. Vincent Liu, Biao Wu, "Stability of *p*-orbital Bose-Einstein condensates in optical checkerboard and square lattices," *Phys. Rev. A* 87, 013635 (2013).

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FA9550-12-1-0079

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The full name of the principal investigator on the grant or contract.

W. Vincent Liu

Program Manager

The AFOSR Program Manager currently assigned to the award

Dr. Tatjana Curcic

Reporting Period Start Date

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Abstract

The overall goal of the original proposal was to develop quantitative theories to understand strongly interacting fermionic atoms in optical lattices. In achieving this goal, the collaborative team addressed a number of previously open questions and theoretical challenges using systematic analytical and numerical analysis which enabled them to make notable accomplishments in the following four directions. First, the team discovered a few new forms of orbital phases in optical lattices, which have no prior analogue from solid-state materials (e.g. a topological ladder, a spin-disordered but orbital ordered state of interacting atoms). Second, they found model systems that introduce the notion of chiral Bose liquid (a state of matter that is neither a normal gas nor a superfluid) and a mechanism to center-of-mass p-wave chiral superfluidity arising from purely s-wave interaction. Third, the team discovered a novel Weyl superfluid state at low temperatures for a three-dimensional dipolar Fermi gas in a rotating external field. This state supports Weyl fermion, a concept originated from particle physics. Fourth, they discovered a new class of edge modes for cold atoms in a periodically driven optical lattice, which have no static analog and lie outside the known periodic table of topological classification. Overall, the completed research projects substantially advanced our understanding of interacting cold gases with broad impacts on the interfaces with condensed matter and particle physics. Applications and experiments of some of the physics notions developed are expected to follow in the future.

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